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Evaluating Pollution from Aquaculture Materials and Developing Sustainable Alternatives to Reduce Marine Environmental Impacts: A Case Study in Vietnam

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Abstract
This study aims to assess the status of marine pollution associated with aquaculture activities in Vietnam, emphasizing the contribution of primitive aquaculture materials—such as Styrofoam floats, wooden cages, and low-grade plastics—to environmental degradation. The research analyzes the pathways through which these materials generate microplastics, chemical leachates, and solid waste, exacerbating coastal and marine pollution. Furthermore, in this work has been proposed that the promising approach highlights the importance of sustainable material innovation, particularly the development and application of high-density polyethylene (HDPE) and other eco-friendly composites, as a strategic solution to mitigate the adverse environmental impacts of aquaculture. The development of sustainable HDPE materials aims to address the urgent challenges of marine plastic emissions from conventional aquaculture practices. Specifically, this study will propose a sustainable HDPE pipe production solution through a technological approach that blends UV-resistant and anti-aging additives at an optimal ratio. The goal is to synthesize durable HDPE materials suitable for application in sustainable marine aquaculture. By integrating technological advancements, policy recommendations, and local implementation strategies, this study provides a scientific foundation for promoting environmentally responsible and economically viable marine aquaculture in Vietnam.
Keywords: HDPE, Stabilizer, Aquaculture Materials, Marine Environment, Sustainable Alternative.

1. Introduction

Vietnam is among the world's leading aquaculture producers, contributing significantly to global seafood supply and national economic growth. With more than 3,200 km of coastline, the country's coastal and marine aquaculture—particularly shrimp, fish, and mollusk farming—has expanded rapidly over the past two decades [1]. However, this development has also generated growing concerns regarding environmental degradation, particularly marine pollution caused by aquaculture activities [2]. The main sources of marine pollution from aquaculture could be came from the pollution of nutrient-rich effluents, organic sludge, chemical residues, and solid waste originating from aquaculture materials [3]. Furthermore, in small- and medium-scale operations, farmers often use primitive, low-cost materials such as Styrofoam (EPS) floats, nylon nets, plastic ropes, and wooden cages coated with tar or paint. These materials are inexpensive and accessible but highly polluting due to their poor durability, low recyclability, and non-biodegradable nature. Under prolonged exposure to UV radiation, salinity, and wave action, they degrade into microplastic particles and release additives and heavy metals into surrounding waters [4].

Some previous research showed the accumulation of plastic debris from aquaculture infrastructure has been documented in coastal regions such as Nha Trang Bay, Phu Yen, and Ha Long Bay, where discarded or fragmented aquaculture gear contributes to the growing problem of marine litter and microplastic contamination. Alongside this, nutrient discharges from uneaten feed and excreta intensify eutrophication, oxygen depletion, and sediment enrichment, degrading coral reefs, mangroves, and seagrass ecosystems. These combined pressures threaten biodiversity and the livelihoods of coastal communities dependent on fisheries and tourism [2]

Therefore, research and development of sustainable aquaculture materials has emerged as one of the most effective and proactive strategies to mitigate marine pollution. Replacing primitive materials with eco-friendly, durable, and biodegradable alternatives can significantly reduce waste generation and plastic leakage at the source [5]. Promising materials include high-density polyethylene (HDPE) modular cages**,** composite floats made from recycled polymers, and bio-based materials derived from bamboo, cellulose, or polylactic acid (PLA) are much attention recently. These alternatives exhibit higher durability and lower fragmentation rates, making them suitable for long-term marine applications. Moreover, adopting a circular economy approaching which used nets, ropes, and floats are collected, recycled, or repurposed—can minimize synthetic debris accumulation in coastal environments. Governmental initiatives combined with public–private partnerships are also essential to accelerate technology transfer, cost reduction, and farmer adoption of sustainable materials. Beyond environmental benefits, such materials improve operational performance by reducing fouling, UV degradation, and maintenance costs [2].

Herein, this study aims to assess the status of marine pollution from aquaculture activities in Vietnam**,** with a focus on the role of primitive materials in pollution generation**,** and to highlight sustainable material research and innovation as a strategic solution for mitigating marine environmental impacts.

2. Sources and characteristics of marine pollution

Marine pollution from aquaculture in Vietnam arises from three interrelated sources: organic and nutrient discharges, chemical residues, and solid waste from aquaculture materials.

2.1 Nutrient and Chemical Pollution

Uneaten feed, metabolic waste, and excessive fertilizer inputs release nitrogen and phosphorus, contributing to eutrophication and algal blooms [6]. Antibiotics and disinfectants, commonly used to prevent disease outbreaks, enter marine environments via effluent discharge, leading to antimicrobial resistance and sediment contamination.

2.2 Pollution from Primitive Aquaculture Materials

Primitive aquaculture materials is one of the important issues that will affect marine pollution when using low-quality, non-durable materials in aquaculture infrastructure. In some small-scale farmers commonly employ Styrofoam floats, nylon nets, plastic ropes, polypropylene feed bags, and wooden cages coated with tar or paint because of their low cost and accessibility. During this period, these materials degrade under sunlight, wave action, and salinity, releasing microplastics, heavy metals, and toxic additives into surrounding waters. Fragments of Styrofoam and torn nets are frequently observed drifting in bays such as Ha Long, Nha Trang, and Phu Yen, where they contribute to marine litter accumulation and threaten marine fauna through ingestion or entanglement. Unlike industrial aquaculture systems, many traditional farms lack waste collection or recycling mechanisms, resulting in direct dumping or abandonment of damaged gear at sea [7]. The short lifespan and poor durability of these primitive materials exacerbate pollution. For instance, Styrofoam floats typically degrade within 6–12 months, releasing thousands of fragments per cage system annually. These fragments disperse widely, forming secondary microplastics that enter food webs via filter-feeding organisms and fish. Moreover, tar-coated wooden structures leach hydrocarbons, affecting benthic organisms and reducing dissolved oxygen levels.

In recent years, waste generated from broken Styrofoam floats used in marine cage aquaculture has increasingly affected the marine environment. To address this issue, the Center for Supporting Green Development (GreenHub) implemented the project “Toward Model Cities for Waste Management in the Northern Coastal Region of Vietnam (Blue Bay Project)”**,** funded by the United States Agency for International Development (USAID**)** through the Development Innovations Group (DIG)**.** The project was carried out from 2018 to 2020 in the Cat Ba Archipelago (Hai Phong City) and Ha Long Bay (Quang Ninh Province)**,** Vietnam. The project piloted the use of Styrofoam floats coated with Line-X material in aquaculture cages in Ha Long Bay to enhance float durability and reduce environmental impacts on seawater quality. This initiative contributed to efforts in reducing plastic waste, particularly Styrofoam waste**,** in Vietnam. Based on the project’s results, experts proposed integrating its outcomes into local policies and programs as part of the Action Plan for Plastic Waste Reduction in the Fisheries Sector [8, 9]**.**

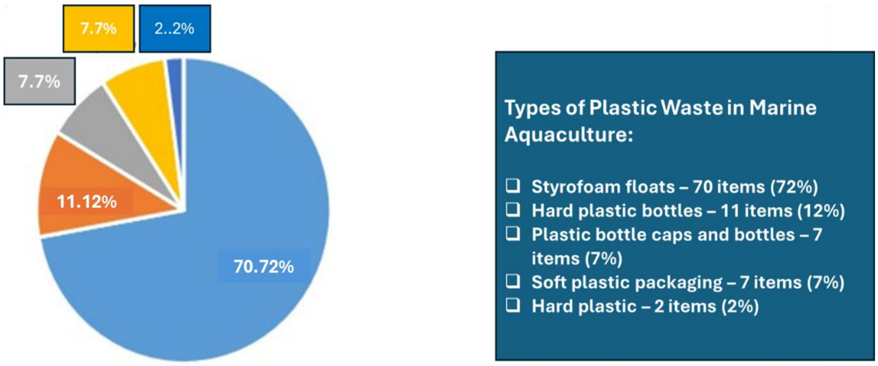

Figure 1. The five most common types of waste found in Ha Long Bay, Vietnam June 2018 [8, 9]**.**

3. Environmental impacts

The cumulative effects of aquaculture waste, including degraded materials—extend beyond localized pollution. High organic loads and nutrient enrichment cause eutrophication, while microplastic and synthetic debris alter sediment composition, impair benthic habitats, and act as vectors for pathogens and persistent organic pollutants [4]. These pollutants reduce ecosystem resilience, degrade water quality, and pose economic threats to tourism and capture fisheries.

4. Analysis of marine plastic waste sources from aquaculture materials in selected Vietnamese coastal areas

4.1. Sources of plastic waste from materials in lobster cage farming

Lobster cage culture occurs from Quang Binh to Binh Thuan provinces with major production in Phu Yen and Khanh Hoa. The two provinces are located in South-Central Vietnam with many enclosed bays that are suitable for the development of shellfish, fish and lobster cage farming. The total number of cages in Phu Yen and Khanh Hoa provinces was 185,166 in 2019, accounting for 97.8% of the lobster cages in Vietnam; production reached 2273 tons, accounting for 95% of the country's lobster aquaculture production [10-11]. Each floating raft is anchored and includes a temporary shelter made from corrugated iron sheets, Styrofoam panels, or plastic boards. In the linked net-cage model, 2–6 plastic jerry cans per cage provide buoyancy. Over time, exposure to seawater and UV radiation causes the plastic to crack, leading to fragmentation and leakage of microplastics into the marine environment [4]. Damaged components are often discarded directly into the sea, especially where waste management systems are lacking.

4.2. Sources of plastic waste from materials in marine fish cage farming

Marine fish farming in sheltered bays typically employs small floating cages (2 × 2 × 2 m or 3 × 3 × 3 m) located at depths of approximately 5 m during low tide. The main sources of plastic pollution in this system are styrofoam (EPS) floats and plastic drums, which provide buoyancy for cages and platforms. EPS floats are often wrapped in woven polypropylene (PP) sheets or plastic tarpaulins to prevent abrasion. Despite their buoyancy, these materials have low durability in seawater and fragment easily after 2–3 years of use, releasing microplastic particles into the marine environment. In practice, many fish farmers continue using degraded floats well beyond their safe service life, leading to severe foam fragmentation and plastic litter. Plastic drums (HDPE) have a longer lifespan (3–5 years) but higher cost. Some local governments, such as in Quang Ninh Province, have introduced administrative measures restricting EPS use in Ha Long Bay to mitigate marine litter [7]. Additionally, polypropylene (PP) ropes are extensively used to link cages, adding to the total plastic input per farming unit.

4.3. Sources of plastic waste from materials in mollusk farming

Mollusk aquaculture, the third-largest aquaculture sector in Vietnam after shrimp and catfish, is rapidly expanding in coastal provinces such as Quang Ninh, Nam Dinh, and Thanh Hoa [1]. The system employs large numbers of plastic ropes, floating barrels, and EPS buoys for hanging baskets or lantern nets. As with fish and lobster farming, these materials degrade under UV and saline conditions, releasing microplastics and fragments into surrounding waters [4]. Given the economic importance of mollusk culture, the widespread use of low-cost floating materials represents a major challenge for sustainable aquaculture development. Plastic fragments from discarded floats and ropes accumulate in coastal sediments, threatening benthic organisms and local ecosystems.

4.5. Estimation of marine plastic waste generated from aquaculture materials in selected Vietnamese provinces

Based on field surveys and direct observations conducted in Quang Ninh, Phu Yen, and Kien Giang provinces, the study identified and quantified the major types of plastic materials commonly used in different aquaculture models. These materials are associated with key farming systems, including intensive shrimp ponds, lobster cages, marine fish cages, and mollusk farming platforms. Plastic materials observed at these sites include high-density polyethylene (HDPE) pond liners, polyvinyl chloride (PVC) pipes, expanded polystyrene (EPS) floats, polypropylene (PP) ropes, and high-density polyethylene (HDPE) barrels. The quantity, lifespan, and replacement frequency of these materials vary by region and farming practice, directly influencing the volume of marine plastic waste generated. The following table presents the primary types of plastic materials used in aquaculture systems across the surveyed coastal provinces of Vietnam:

Table 1. Types of plastic materials used in aquaculture models in Quang Ninh, Phu Yen, and Kien Giang, Vietnam [12]

TT	Materials	HDPE	PP	PE	PET	PVC	PA	EPS	LDPE-FOAM, STYROFOR
I	**Brackish water shrimp farming**								
1	Pond liner	X							
2	Pipe canopy	X		X					
3	Water inlet and outlet pipes			X		X			
4	Siphon pipe					X			
5	Aeration hose system			X					
II	**Cage fish farming**								
1	Aquaculture net			X					
2	Float								X
3	Plastic barrel	X							
4	Binding rope			X					
5	Mooring rope		X						
III	**Lobster Cage Farming**								
1	Cage net			X			X		
2	Plastic buoy							X	
3	Plastic barrel	X							
4	Binding rope			X					
5	Mooring rope		X						
IV	**Mollusk Aquaculture**								
1	Plastic basket	X		X					
2	Binding rope			X					
3	Rope		X						
4	Float							X	
5	Plastic barrel	X							

In aquaculture infrastructure, plastic materials are widely used for constructing cages, rafts, and floating systems. In Quang Ninh Province, it is estimated that approximately 10 million expanded polystyrene (EPS) floats are currently in use, each with an average lifespan of only 2–3 years These floats are typically employed to support cage and raft aquaculture systems but degrade rapidly under marine conditions, leading to fragmentation and microplastic release into the surrounding environment [4]. Fish cages are commonly made from nylon nets, which generally have a lifespan of 3 to 5 years before replacement is required. The short service life of these low-cost, low-quality plastic materials—such as EPS, nylon, and polypropylene (PP)—reflects their widespread availability and affordability. They are sold across coastal provinces and are easy to install, requiring no advanced technical expertise. Such materials are well suited to calm inland or estuarine waters, where mechanical stress and wave action are minimal.

In recent years, large-scale aquaculture investors have shown increasing interest in improving infrastructure quality. The introduction of high-density polyethylene (HDPE) materials has marked a significant advancement in aquaculture engineering. HDPE possesses superior flexibility and durability, adapting to various terrains and substrates while withstanding water depths exceeding 3 meters [13]. HDPE fish cages are reported to have a lifespan of up to 50 years, offering exceptional resistance to corrosion, UV degradation, and mechanical stress [1]. Consequently, HDPE-based aquaculture cages and floating systems have become viable for offshore, bay, island, and hydropower reservoir farming applications. The transition from primitive EPS-based materials to HDPE modular cages represents an important step toward sustainable and long-term aquaculture development in Vietnam, contributing to both pollution reduction and enhanced production efficiency [2][13]

5. Propose Management Strategies and Material Innovation

The use of high-density polyethylene (HDPE) cages for offshore aquaculture has been successfully implemented in many countries worldwide, demonstrating high productivity, enhanced safety, and superior durability compared with traditional cage systems [1]. The sustainability of HDPE materials arises from the inclusion of specific additives during the production process, which strengthens molecular bonds and improves resistance to environmental degradation. These modifications enhance mechanical performance and extend the service life of HDPE compared to conventional materials such as wood, steel, or nylon. Advantages of Sustainable HDPE Materials in Aquaculture such as: (i) Flexibility and Adaptability, (ii) Waterproof and Safe Buoyancy, (iii) UV, Corrosion, and Oxidation Resistance (iv) Lightweight and Easy Installation, (v) Versatile Dimensions and (v) Cost Efficiency and Longevity. From the above analysis, marine plastic emissions from aquaculture activities represent an urgent and practical issue, as Vietnam still lacks technological and management solutions to effectively address this problem amid worsening environmental pollution and declining aquatic resources. Meanwhile, the potential for sustainable aquaculture development remains significant and requires greater attention. Therefore, one feasible solution to reduce marine plastic waste in aquaculture is to research and develop sustainable materials to replace traditional ones. This approach focuses on optimizing the formulation and additive composition to extend the lifespan of HDPE materials in line with the circular economy concept, enabling their application in aquaculture systems.

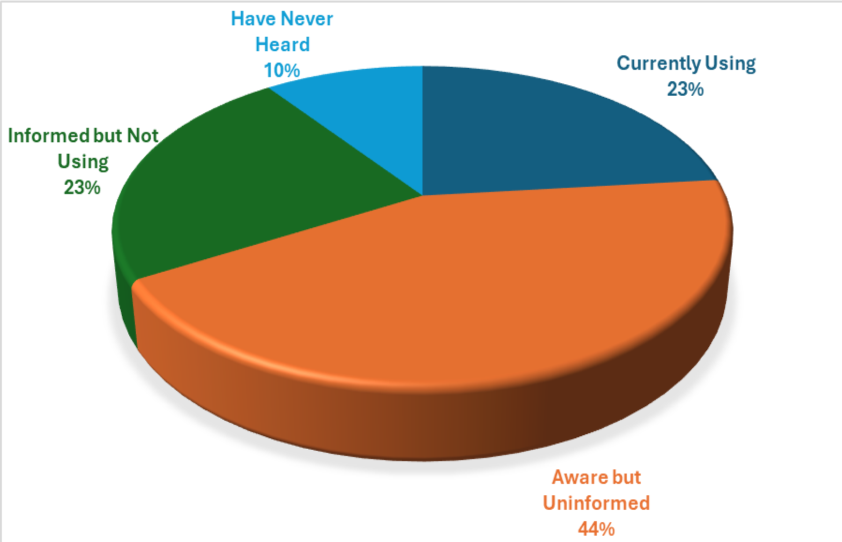

Figure 2. Awareness level of information about HDPE cages.

Figure 3.5 shows that the results of survey about overall awareness level of HDPE floating cages is relatively high. Among the respondents, 7 households (23.3%) reported that they are currently using them, 13 households (43.3%) had heard about them but had not explored further, 7 households (23.3%) had researched them but had not applied the technology, and only 3 households (10.0%) had never heard of them. This indicates that HDPE cages have achieved a certain level of recognition within the community; however, about one-third of the households remain at the stage of merely "having heard" without deeper understanding.

The development of sustainable HDPE materials aims to address the urgent challenges of marine plastic emissions from conventional aquaculture practices. Specifically, this study will propose a sustainable HDPE pipe production solution through a technological approach that blends UV-resistant and anti-aging additives at an optimal ratio. The goal is to synthesize durable HDPE materials suitable for application in sustainable marine aquaculture.

The mechanism of UV stabilizers and anti-aging additives incorporated into HDPE pipes to synthesize sustainable HDPE is described as follows:

Antioxidants:

Several studies have reported the quantification of migrating antioxidants and their degradation products from various polymers under different conditions. However, antioxidant emissions have been extensively studied mainly in PP and LDPE cases [14-15]. Noguerol-Cal *et al.* concluded that the exposure concentration values of the antioxidants BHT and Irganox 1010 were below their specific migration limits established in Directive 2002/72/EC [16-17]. For HDPE, the antioxidant content used—less than 2% by weight—fully meets the requirements for preventing oxygen penetration and surface oxidation of the product. Since the antioxidants are encapsulated by the outer HDPE layer, their environmental impact is almost negligible and difficult to detect.

UV Stabilizers:

Ultraviolet stabilizers generally include hindered amine light stabilizers (HALS) such as Tinuvin 622, Tinuvin 765, and Chimasorb 944 [18-19]. Begley *et al*. investigated the migration of Tinuvin 234 (T234) from PET into Miglyol, aqueous ethanol, and isooctane, concluding that the diffusion rate of Tinuvin 234 from PET is very slow [20]. Studies indicate that for HDPE, the use of UV stabilizers at concentrations between 0.1% and 1.0% by weight—encapsulated within the molten polymer matrix during processing—results in a very low potential for environmental release.

5. Conclusion and Future Directions

The marine pollution problem linked to aquaculture in Vietnam is not only a consequence of nutrient discharge but also of the pervasive use of primitive aquaculture materials that fragment, degrade, and persist in marine ecosystems. Addressing this issue requires an integrated approach combining material innovation, improved waste collection, and policy incentives for sustainable practices. Therefore, the proposed sustainable HDPE production technology combines both UV stabilizers and antioxidants to harness their synergistic protective mechanisms within the HDPE matrix. This integrated additive approach represents a technologically feasible, economically viable, and environmentally friendly solution for developing durable materials for sustainable marine aquaculture.

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